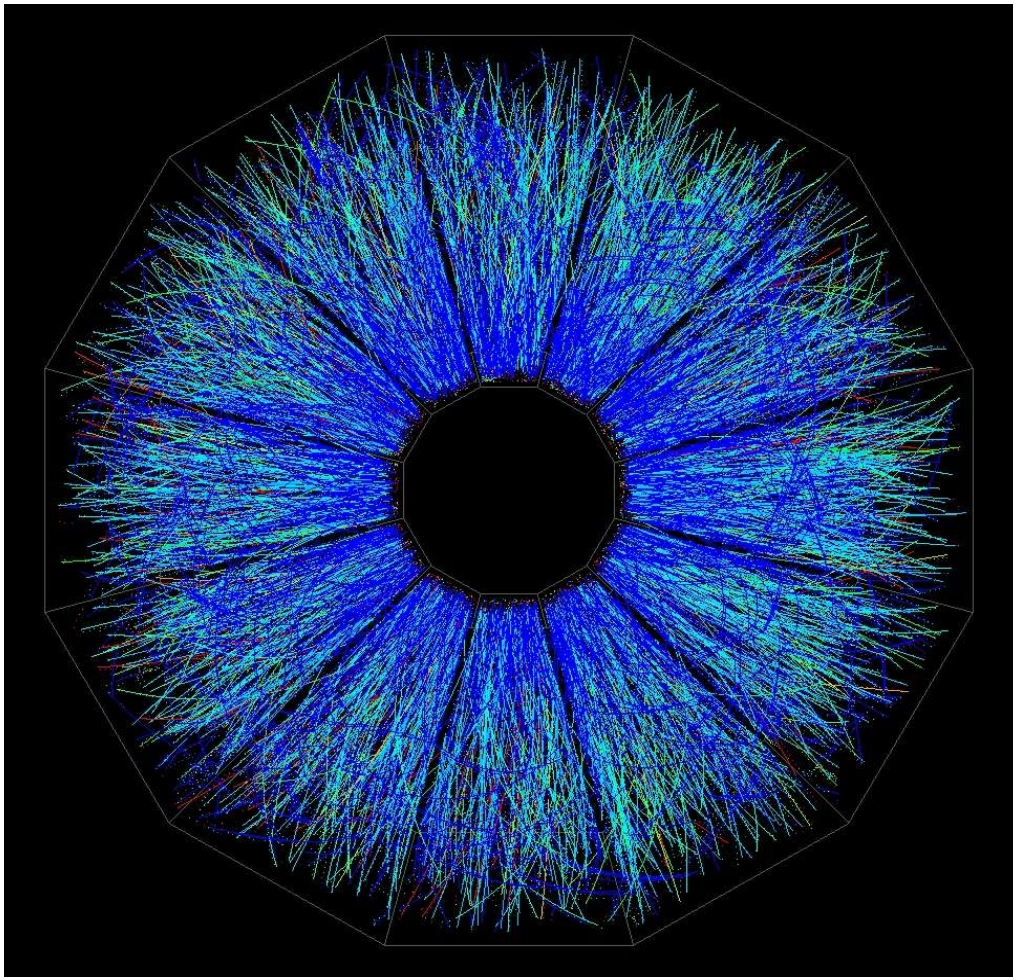
STAR

# Hard Probes at STAR



James Dunlop
Brookhaven National Laboratory
for the STAR collaboration

BROOKHAVEN NATIONAL LABORATORY

# Towards precision in high $p_T$ phenomena

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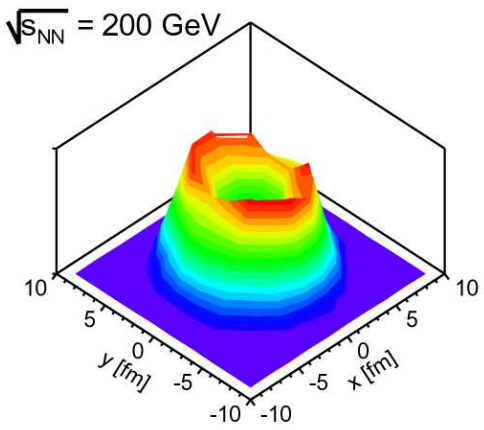
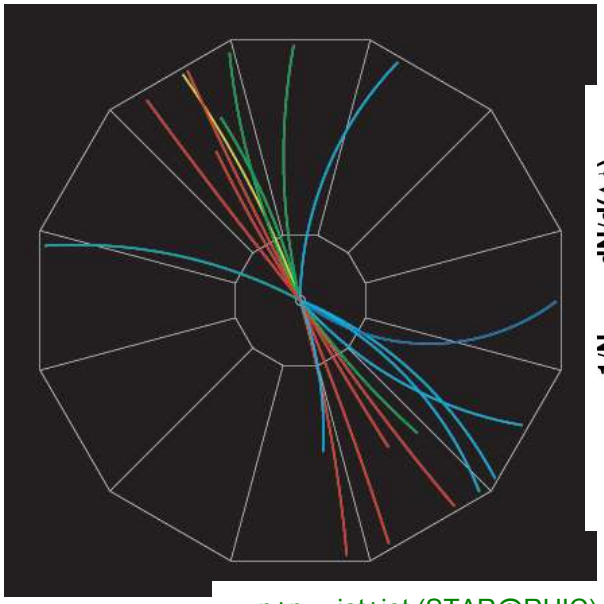
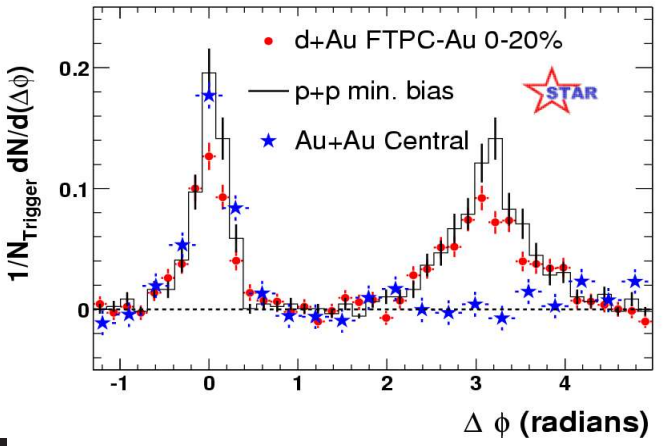
*A. Dainese et al, Eur. Phys. J. C38(2005) 461*



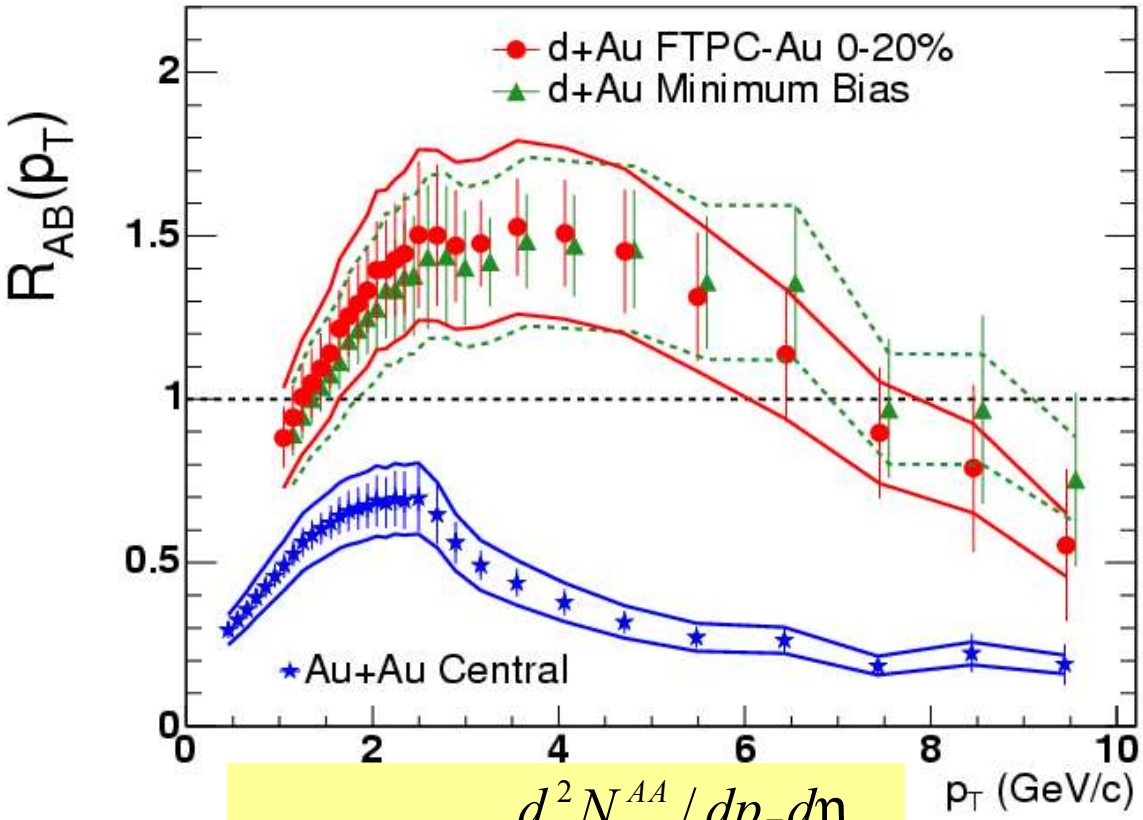
p+p →jet+jet (STAR@RHIC)

*J. Adams et al, Phys. Rev. Lett. 91 (2003) 072304*




- Medium is dense: how to make this more quantitative?
  - Advance the understanding of inclusive suppression
    - Cu+Cu: precise variation of geometry
    - Hadron identification to 10 GeV/c: recombination contributions
  - Raise $Q^2$: properties of clean dijet signatures
  - Decrease coupling of probe to medium: $\gamma$ and heavy flavor

# Inclusive Suppression




$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

*J. Adams et al, Phys. Rev. Lett. 91 (2003) 072304*

Binary collision scaling p+p reference

Suppression an established probe of the density of the medium

# Inclusive Suppression: $R_{AA}$ in Cu+Cu

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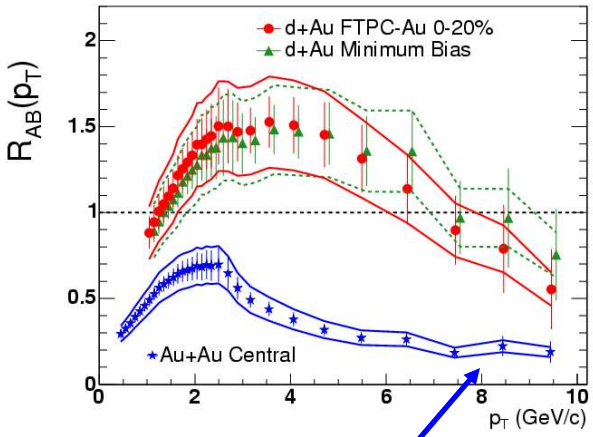
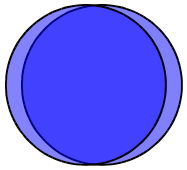
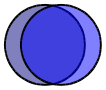
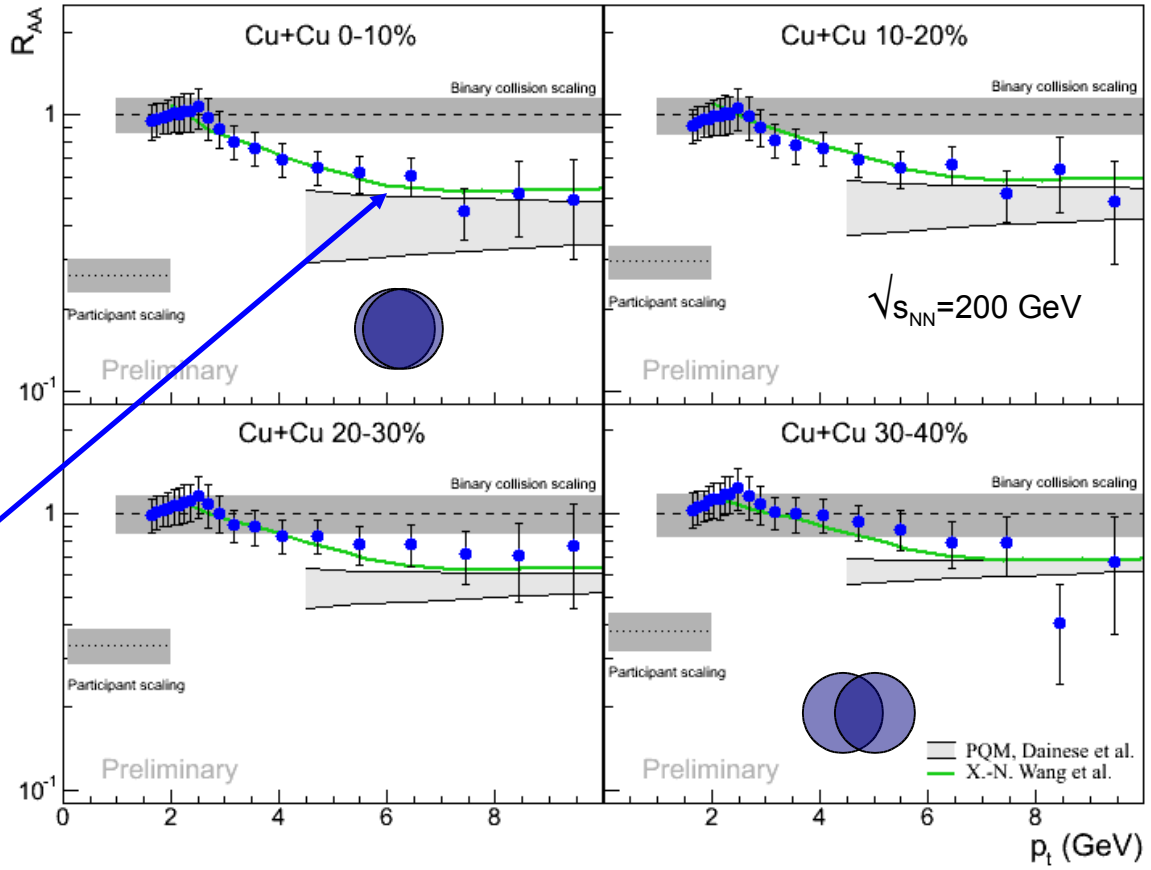


Au+Au
A=197



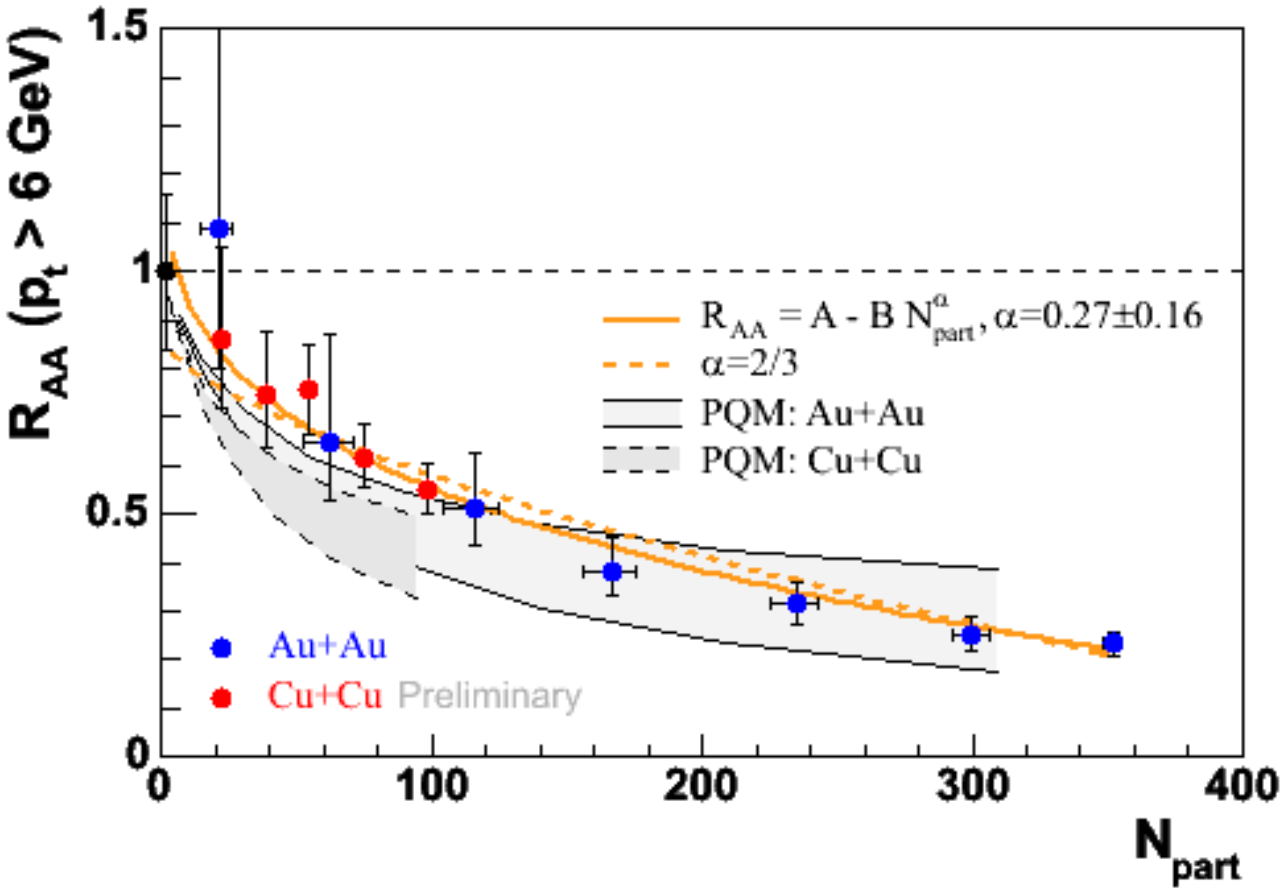
Cu+Cu
A=63




From Au+Au to Cu+Cu: change collision geometry in precise, controlled way
Result: Cu+Cu suppressed, but less so than Au+Au

***See poster, van Leeuwen (91)***

# Geometrical Dependence of $R_{AA}$

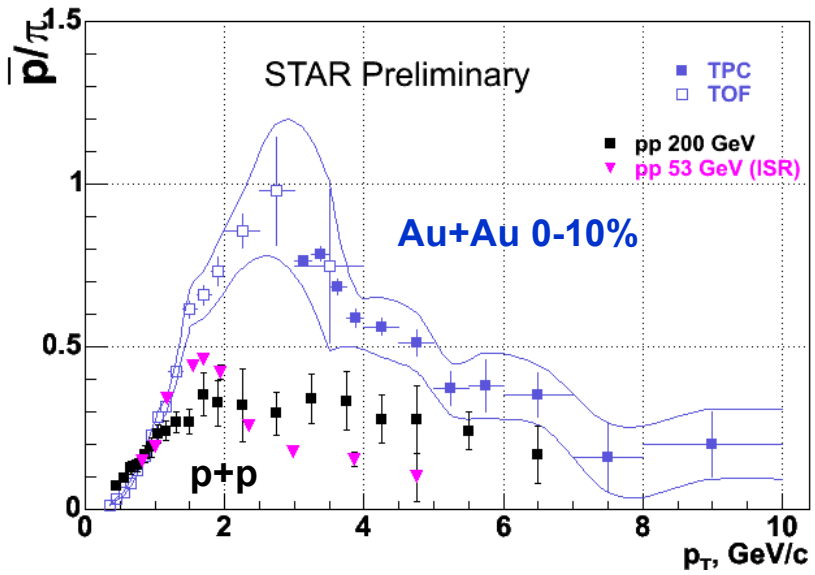


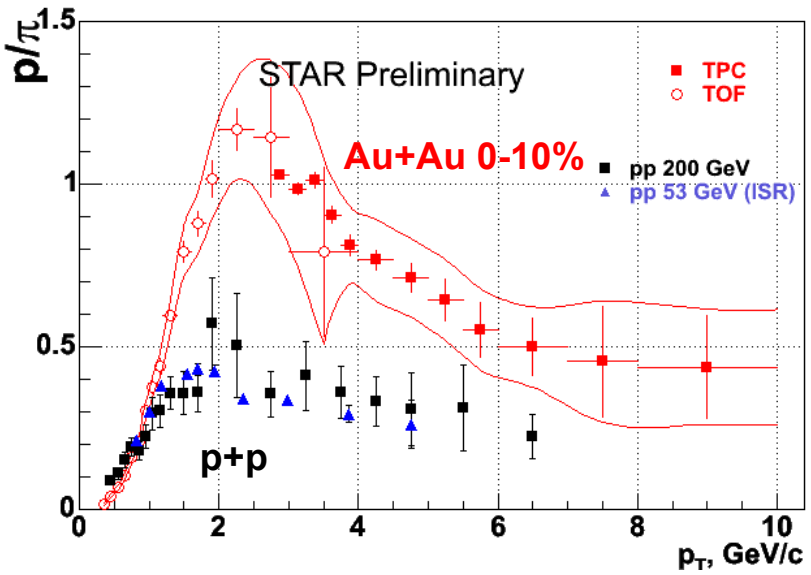

- $R_{AA}$ scales smoothly from Au+Au through Cu+Cu to p+p
  - With exception of p+p, uncertainties dominated by Glauber calculation
- Scaling prefers $N_{part}^{1/3}$, though $N_{part}^{2/3}$ not strongly excluded

***See poster, van Leeuwen (91)***

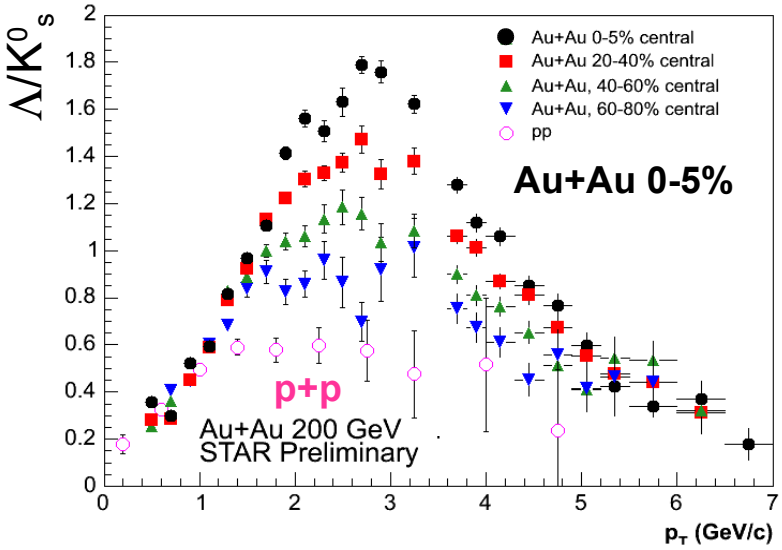
# Baryon enhancement

**STAR**



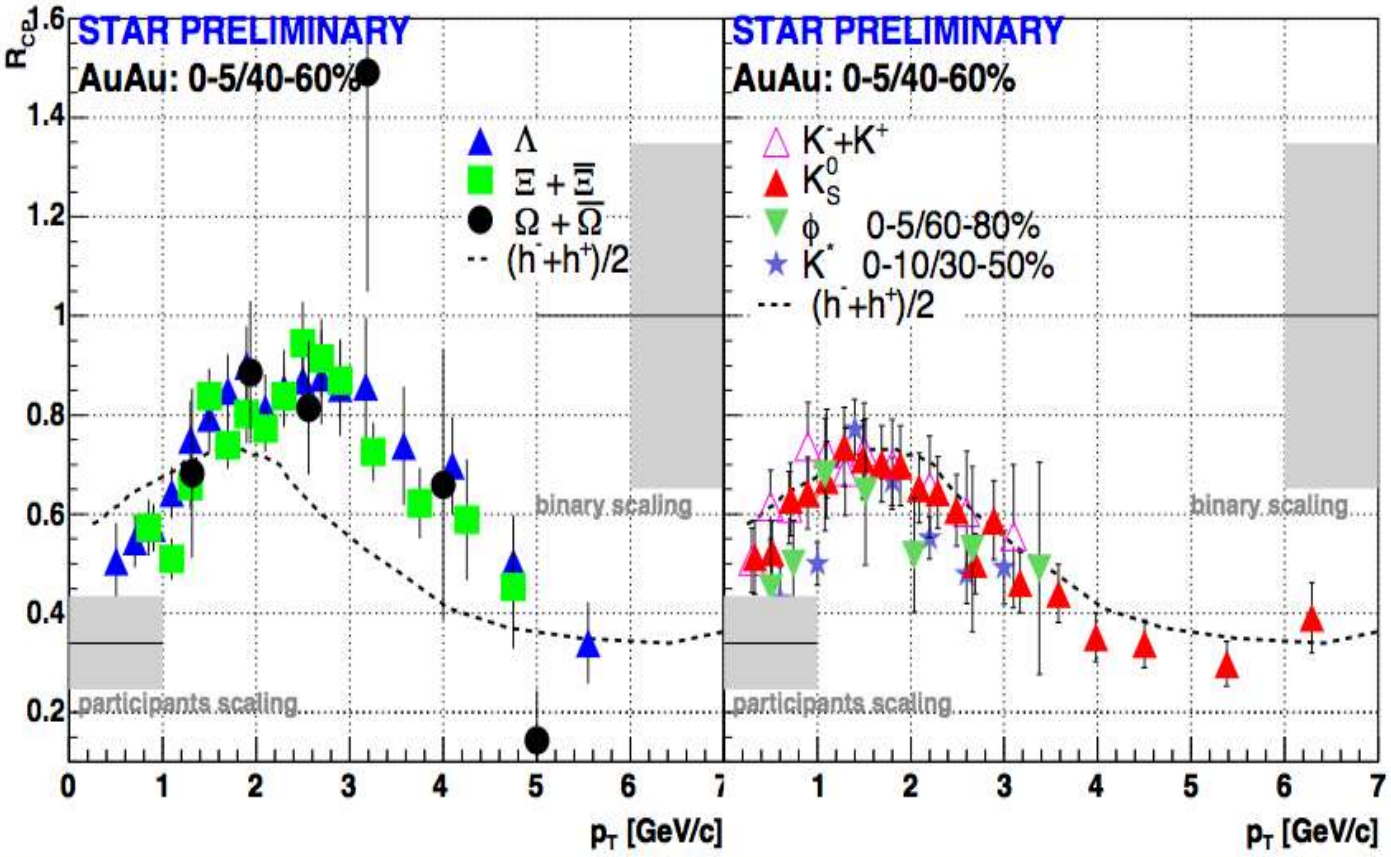




- Large enhancement in baryon/meson ratios in central Au+Au collisions
  - Maximum at $p_T$~3 GeV/c, after which approach towards p+p
- Indication of dominant non-fragmentation contribution
- At what $p_T$ is this contribution no longer dominant?




*See talk, Barannikova(1a) and Salur(5a)*

# Year 2 Baryon $R_{CP}$




- Year 2: clear baryon/meson separation at intermediate $p_T$
  - K* and $\phi$ have mass ~proton, but $R_{CP}$ of a meson
- Consistent with constituent quark recombination as dominant mechanism
- At what $p_T$ is this contribution no longer dominant?
  - Indications of approach for $p_T$>~5 GeV/c, but uncertainties large

# Identified Particle $R_{CP}$

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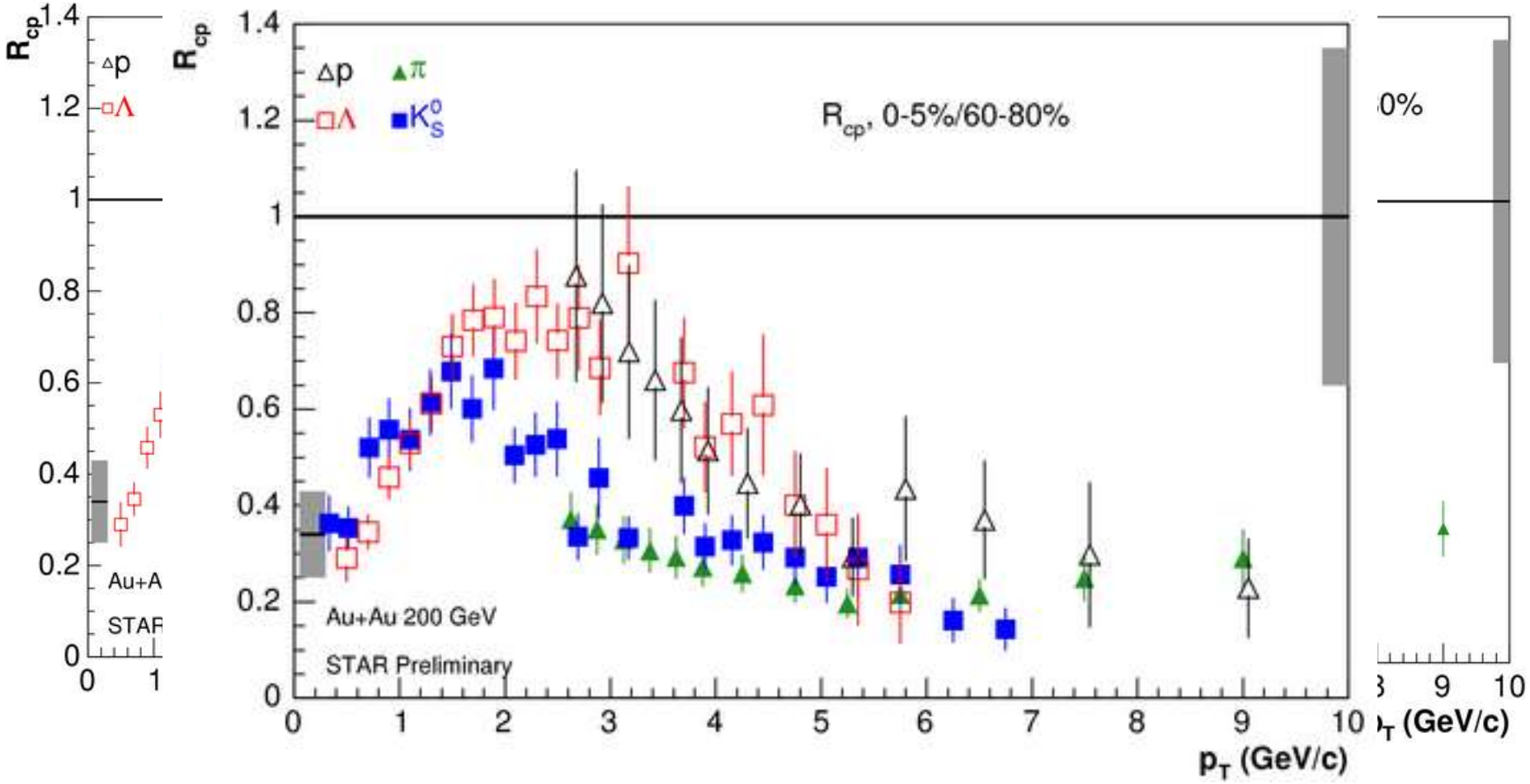


- $\phi$ definitively follows $K^0$ at intermediate $p_T$ : mass is not the source
- All particles consistent for $p_T$>~5 GeV: dominance of fragmentation?

***See talks, Barannikova(1a), Cai(1a), Salur(5a)***

# $R_{AA}$ of Strange Particles

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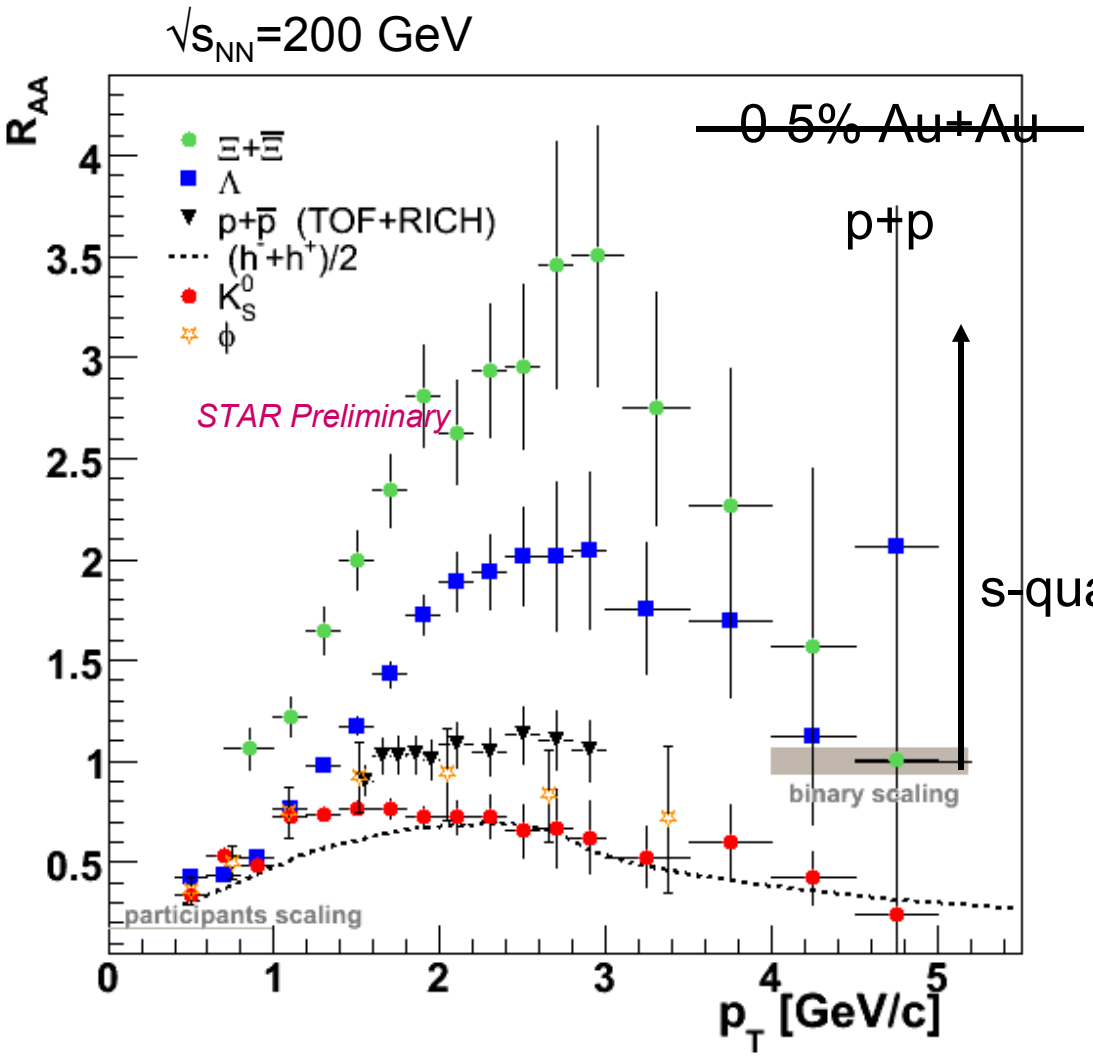



A note: $R_{AA} \neq R_{CP}$

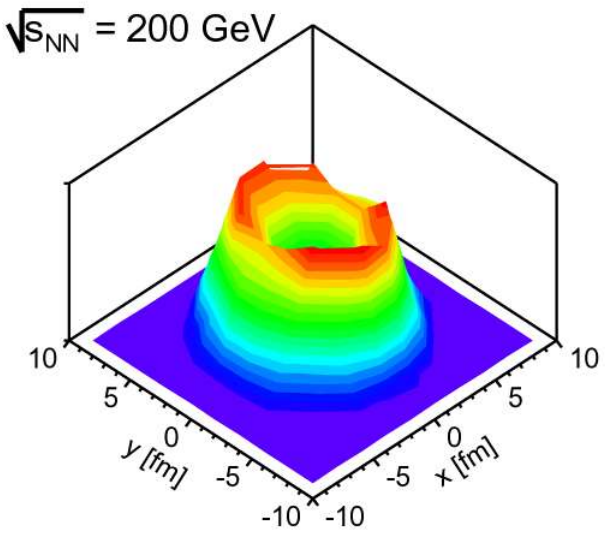
While $R_{CP}$ common across baryons, clear separation in $R_{AA}$, increasing with increasing strangeness content

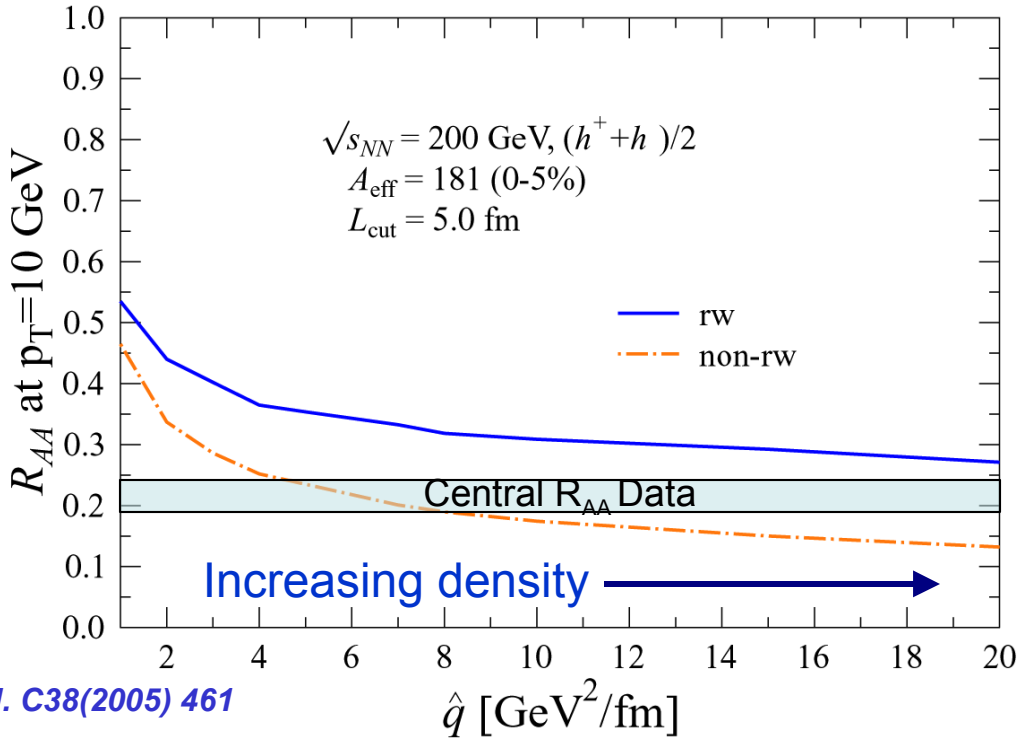
Related to canonical strangeness suppression in p+p? Other mechanisms?

*See talk, Salur(5a)*

# The Limitations of $R_{AA}$

*K.J. Eskola, H. Honkanken, C.A. Salgado, U.A. Wiedemann, Nucl. Phys. A747 (2005) 511*




*A. Dainese, C. Loizides, G. Paic, Eur. Phys. J. C38(2005) 461*

Surface bias leads effectively to saturation of $R_{AA}$ with density

Challenge: Increase sensitivity to the density of the medium

# Emergence of away-side peak

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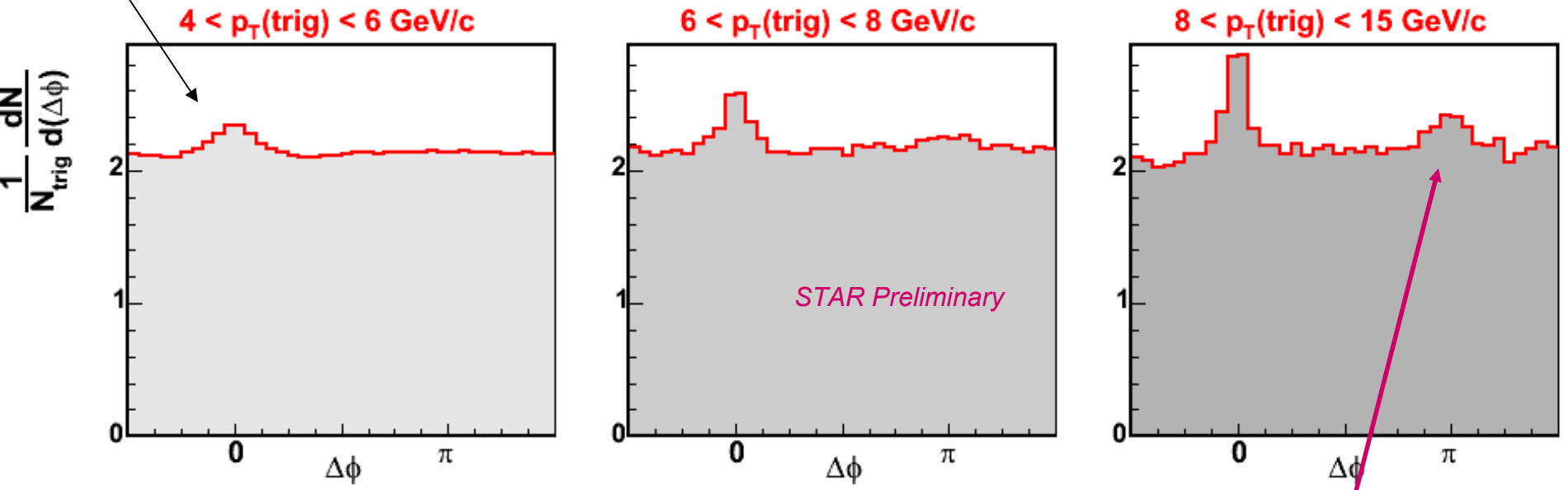
Equivalent to year 2 analysis

**Au+Au, 0-5%**




$p_T$(trig)

$p_T$(assoc) > 2 GeV/c

High statistics year 4 dataset allows increase in $Q^2$

Emergence of the away side peak with increased trigger $p_T$

*See talk, Magestro(3b)*

# Emergence of dijets

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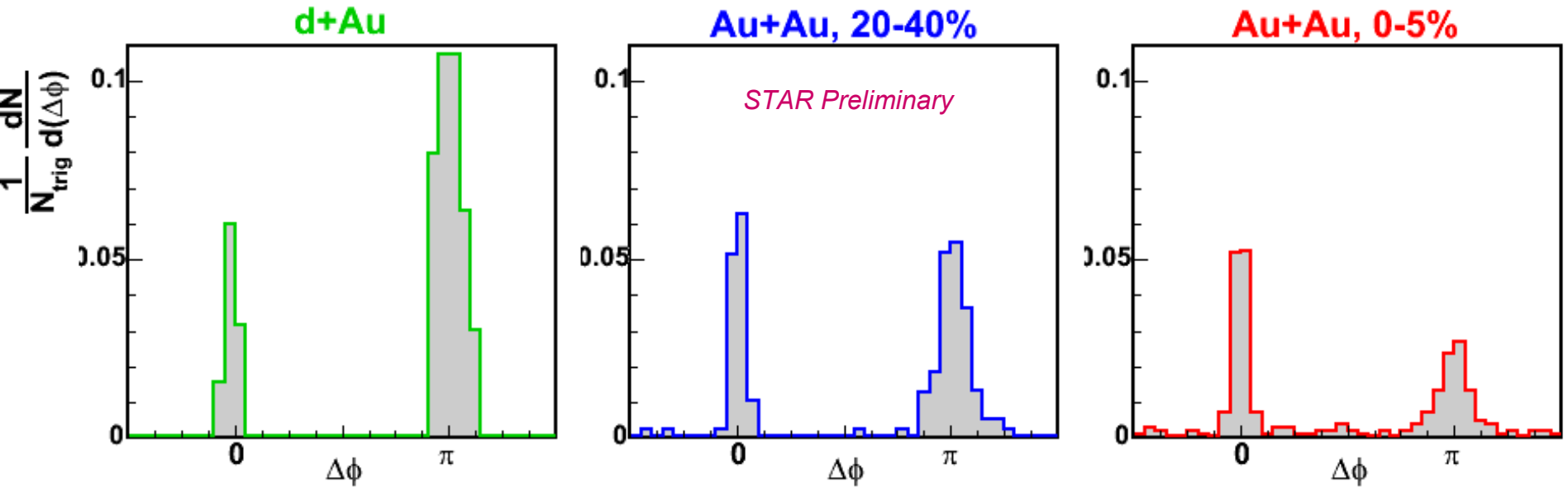
$8 < p_T(\text{trig}) < 15$ GeV/c

$p_T(\text{assoc}) > 6$ GeV




Increase associated $p_T$ threshold also

*For the first time: clear jet-like peaks seen on near and away side in central Au+Au collisions*

*See talk, Magestro(3b)*

# Observation 1 on away-side peaks: Widths

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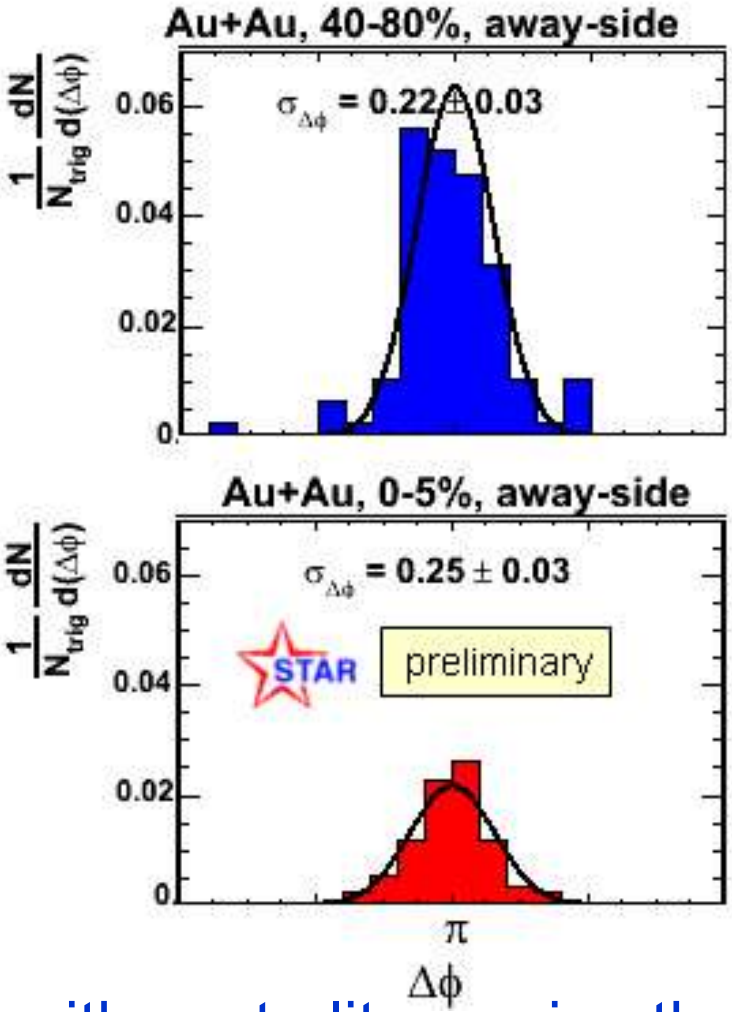
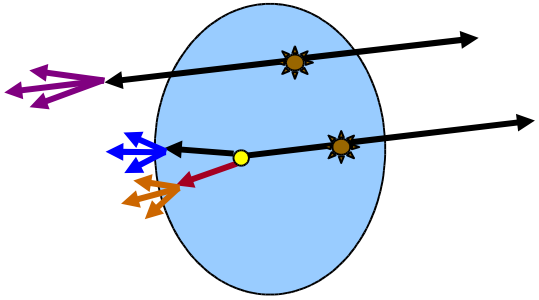
Away-side widths similar for central, peripheral

$8 < p_T(\text{trig}) < 15$ GeV/c

$p_T(\text{assoc}) > 6$ GeV



Widths unchanged with centrality: seeing those partons that fragment in vacuum?

*See talk, Magestro(3b)*

# Observation 2 on away-side peaks: Yields

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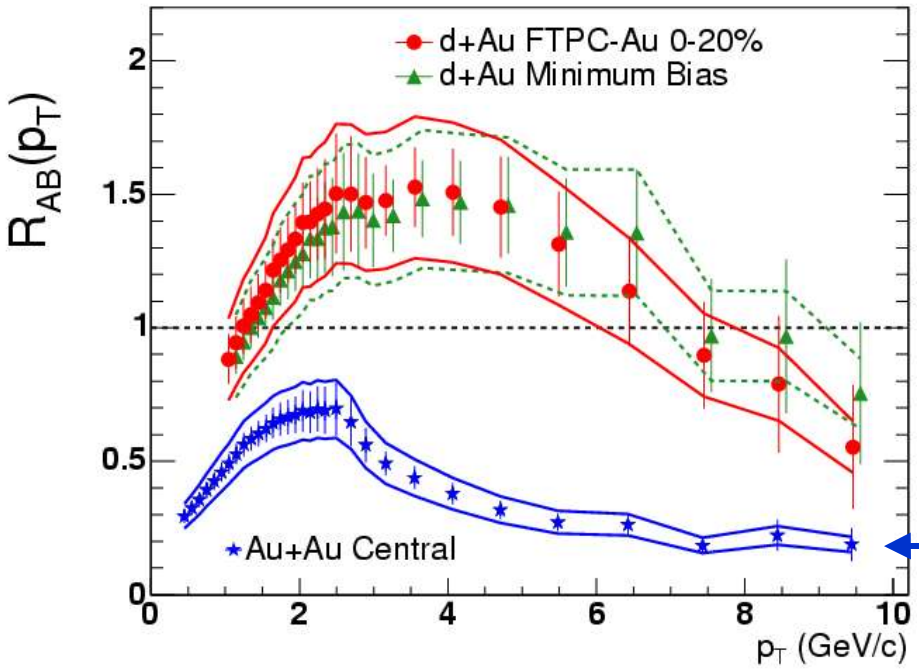
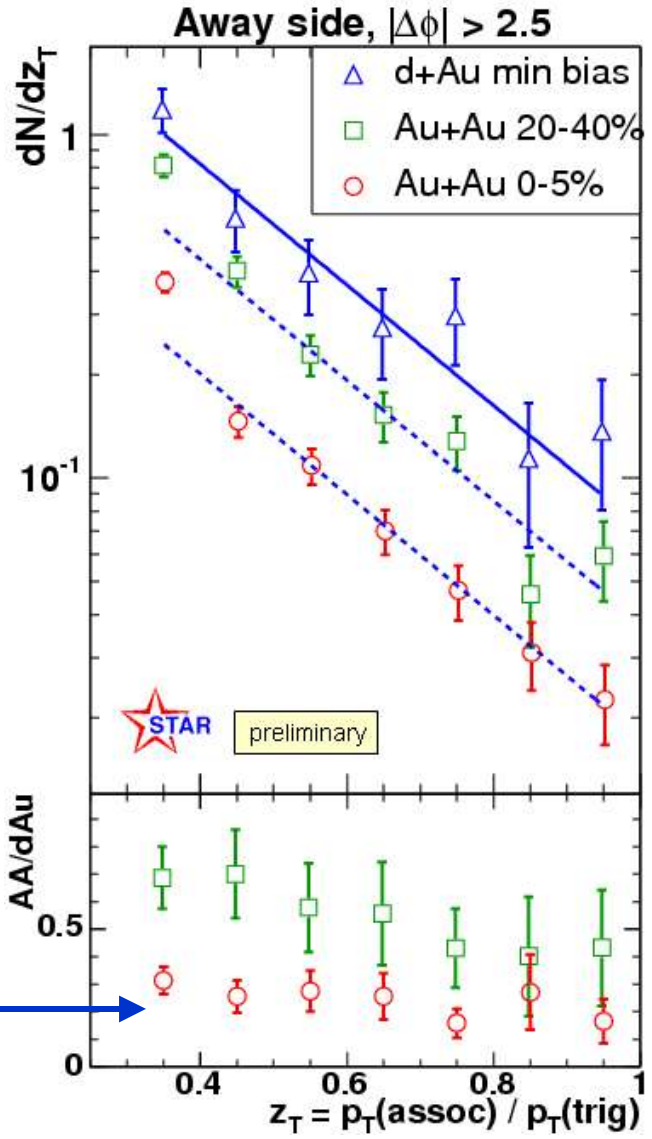
Away-side yield strongly suppressed to level of $R_{AA}$

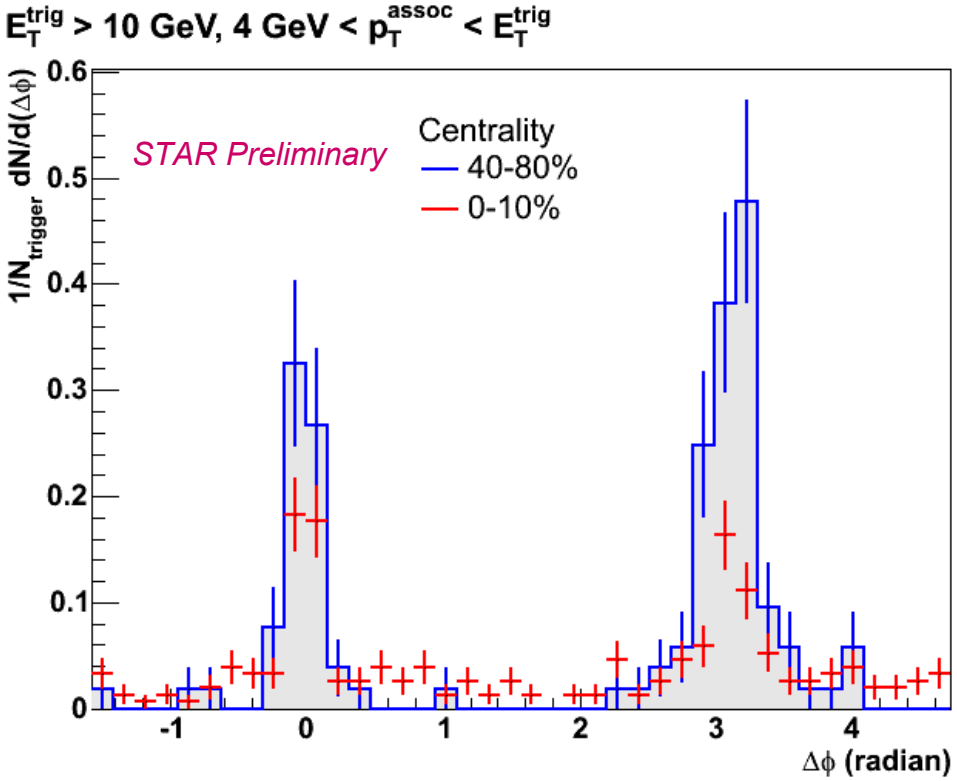
No dependence on $z_T$ in measured range




*See talk, Magestro(3b)*

# Changing the probe: towards γ-jet in Au+Au




- Direct γ does not couple to medium or fragment into jets
  - remove from trigger both surface bias, fragmentation uncertainty in $Q^2$
- Correlations triggered on γ: clear near and away-side peaks
- Strong contamination remains from $\pi^0$ decay daughters
  - Work in progress to separate out direct γ

*See talk, Dietel(3b)*

# Charm production

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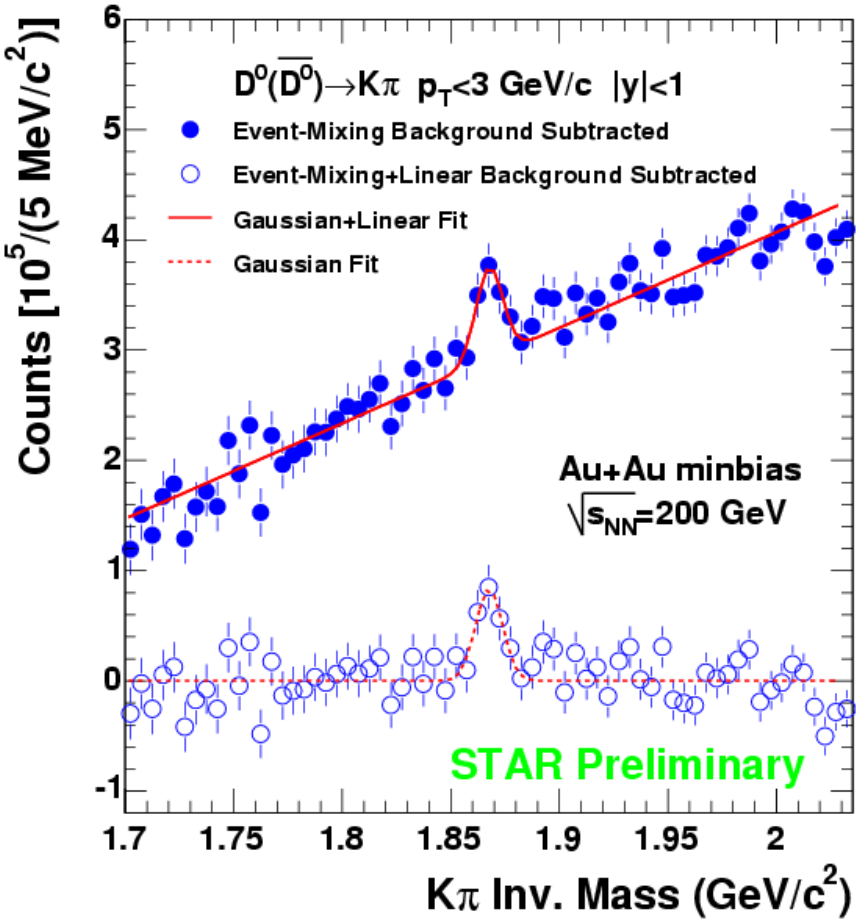


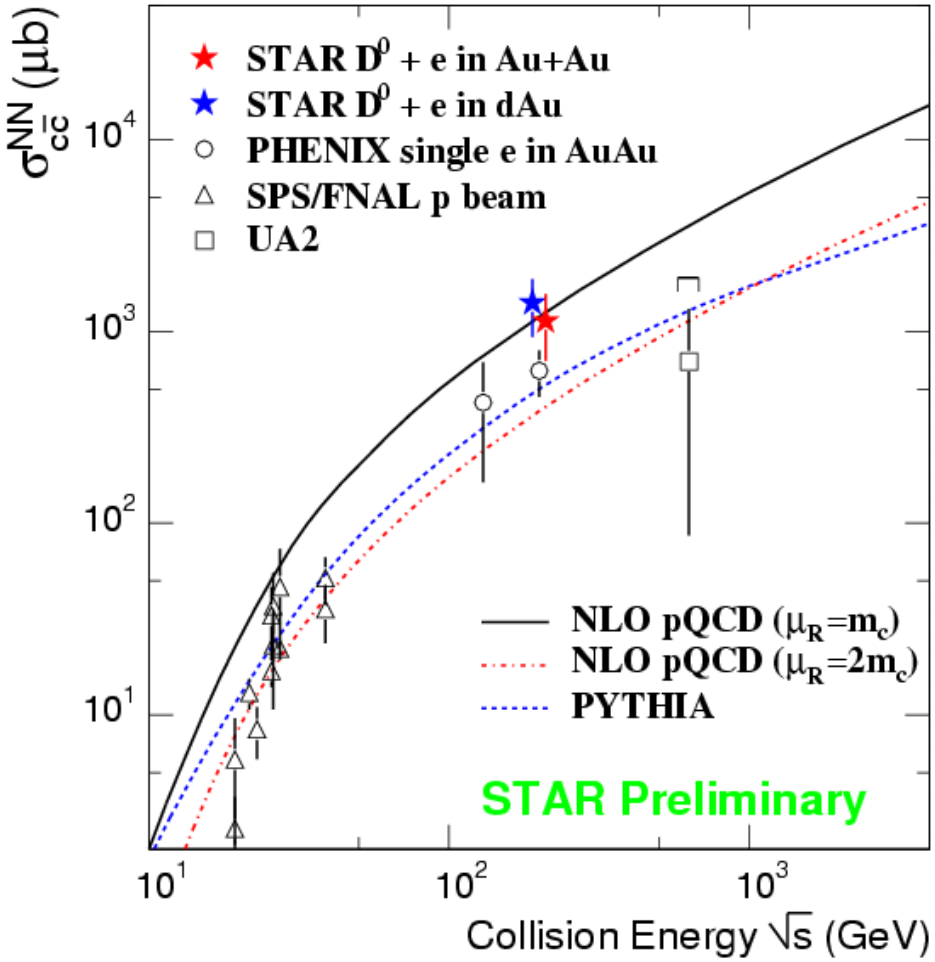


- First direct measurement of open charm in Au+Au Collisions
- Total charm cross-section in Au+Au: $N_{binary}$ scaling from d+Au
- What are the implications of cross sections for J/ψ? *See talk, Zhang(5c)*

# Expectation: Radiative Energy Loss of Heavy Quarks

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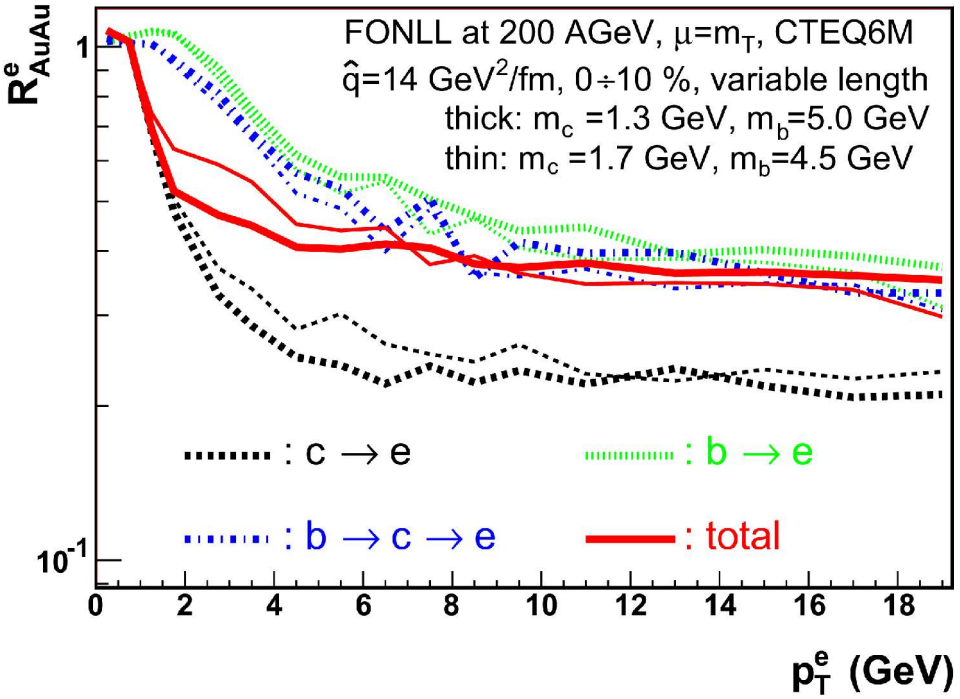
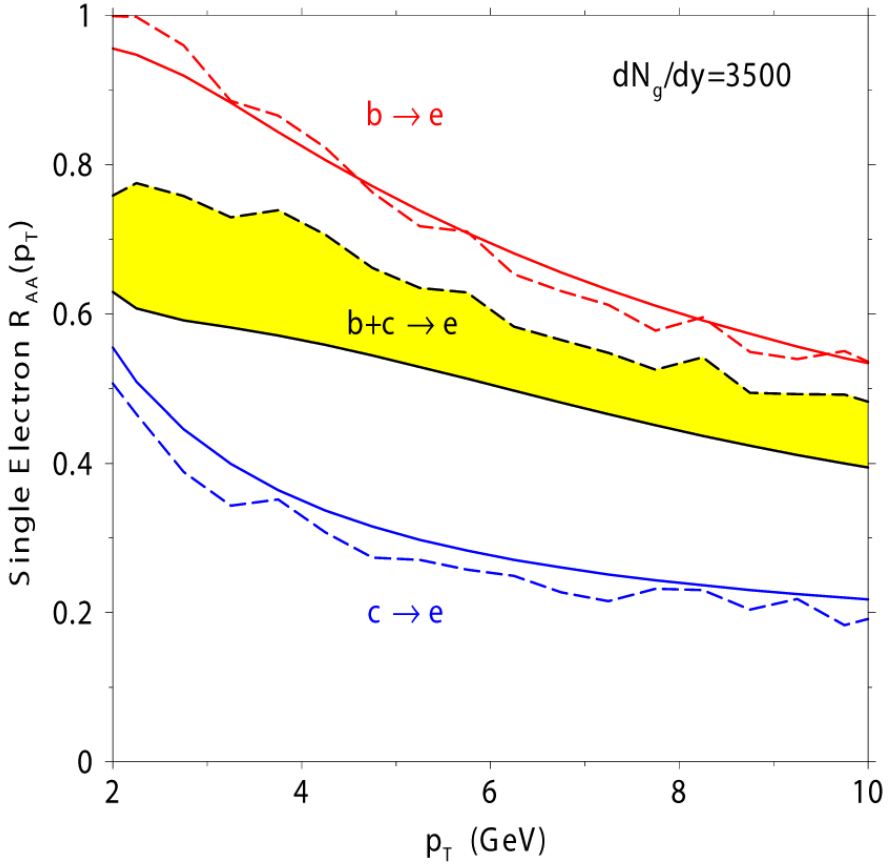
N. Armesto et al., private communication




*See also Armesto et al, Phys. Rev. D71 (2005) 054027*

Djordjevic et al, nucl-th/0507019




- Coupling of heavy quarks to the medium reduced due to mass
- Expectation: even for high medium density, higher $R_{AA}$ for single electrons from heavy flavor than for light hadrons

# Alternative scenario: collisional contribution

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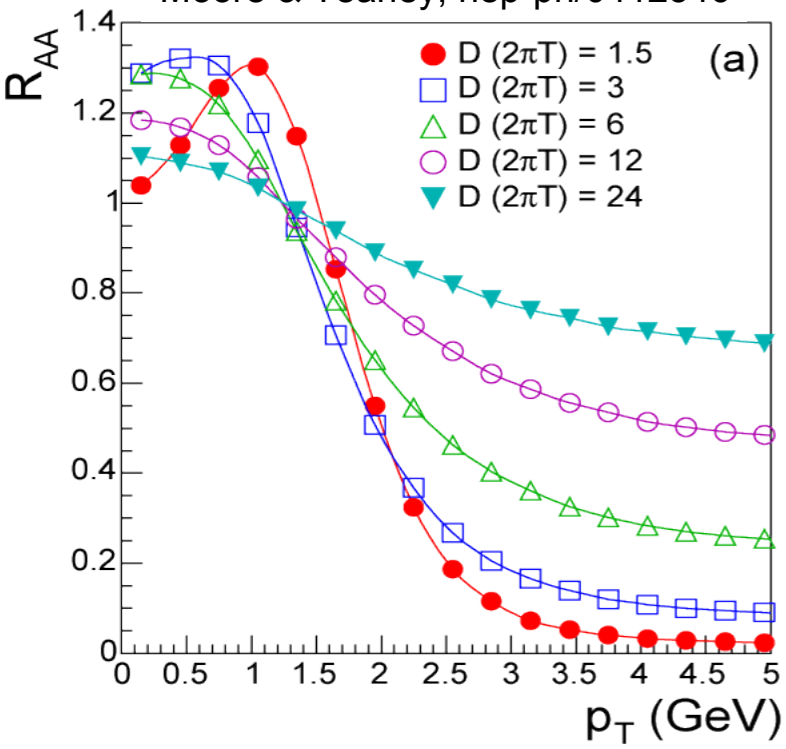
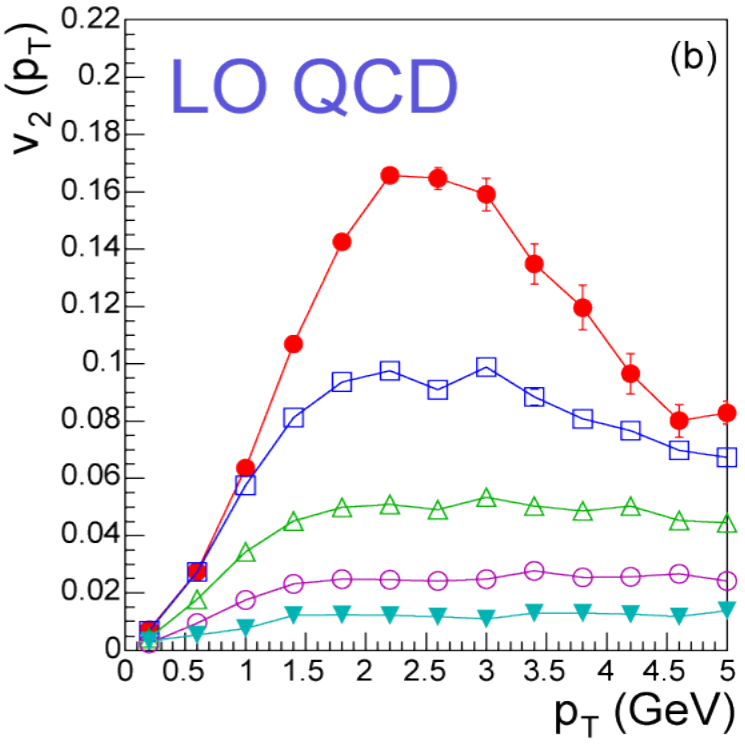
Moore & Teaney, hep-ph/0412346



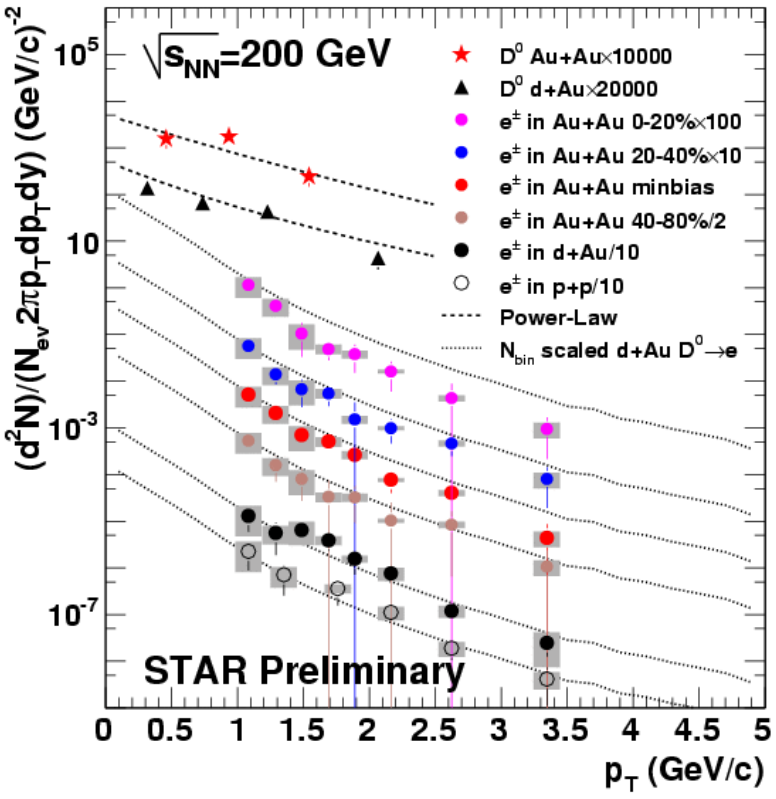




AMPT:
(C.M. Ko)

← σ=10 mb
← σ=3 mb
← pQCD

Large collisional (not radiative) interactions also produce large suppression and $v_2$

# Charm in Au+Au




- Important test of radiative picture: reduction in energy loss from heavy quark mass
- Non-photonic electrons dominantly from charm decay
- Suppression in Au+Au relative to d+Au

*See talk,Zhang(5c)*

# Heavy Flavor $R_{AA}$

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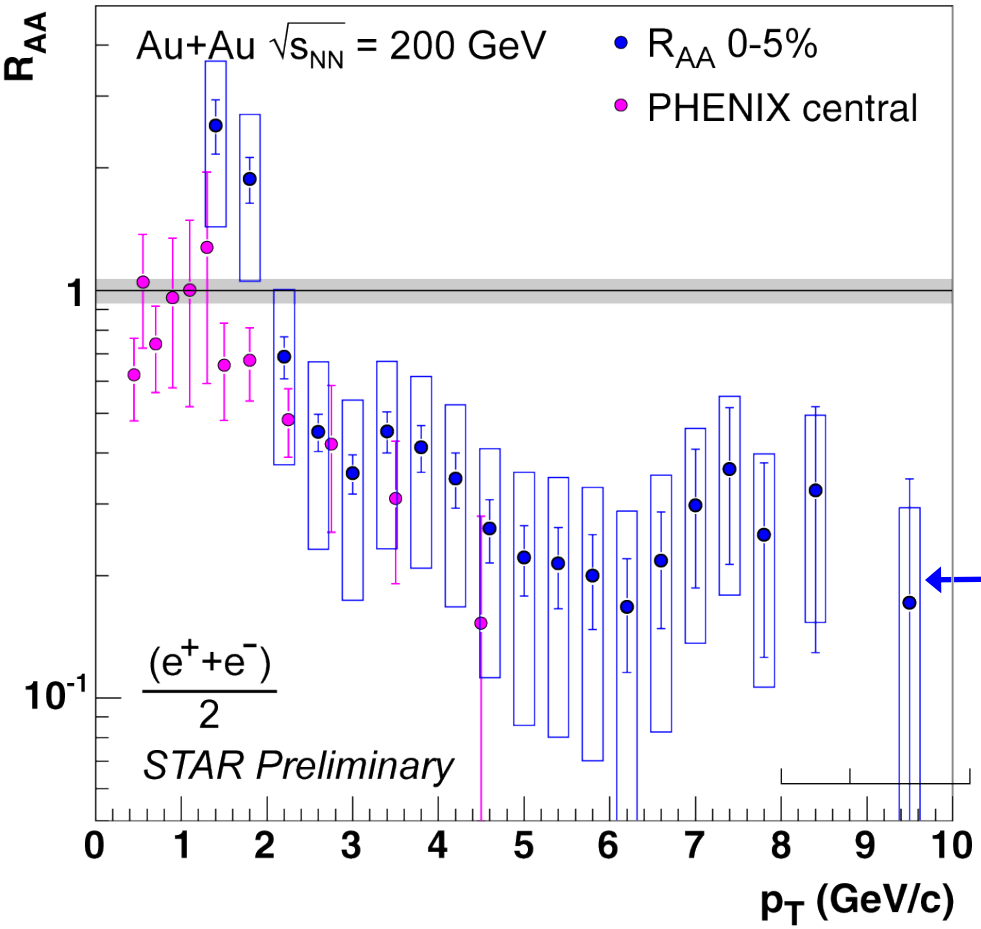
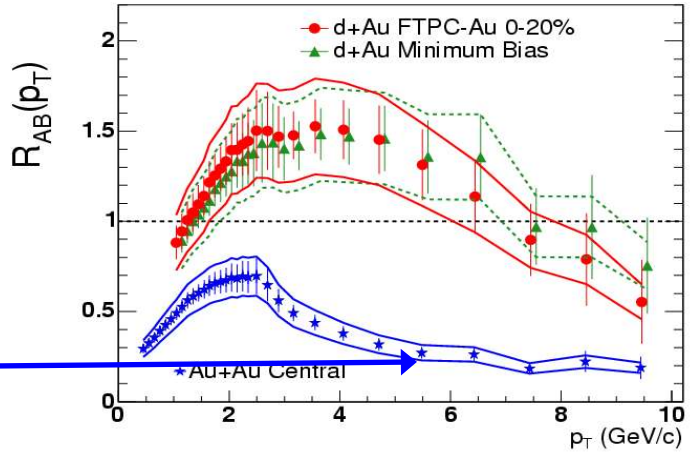



Charged Hadron $R_{AA}$




- $R_{AA}$ to 10 GeV/c in non-photonic electrons
- Suppression is approximately the same as for hadrons
- B contribution? Challenge for radiative picture?

*See talk,Bielcik(5c)*

# Charm $v_2$

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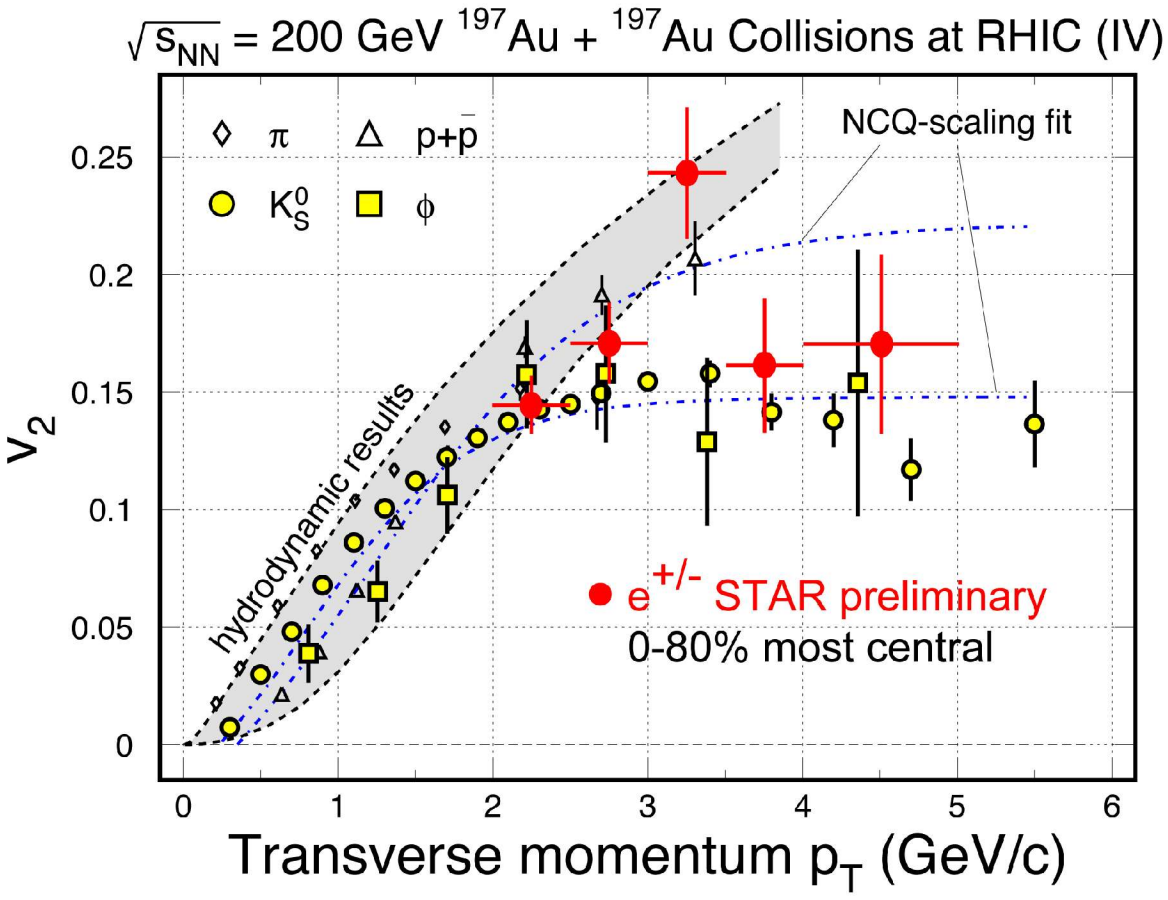
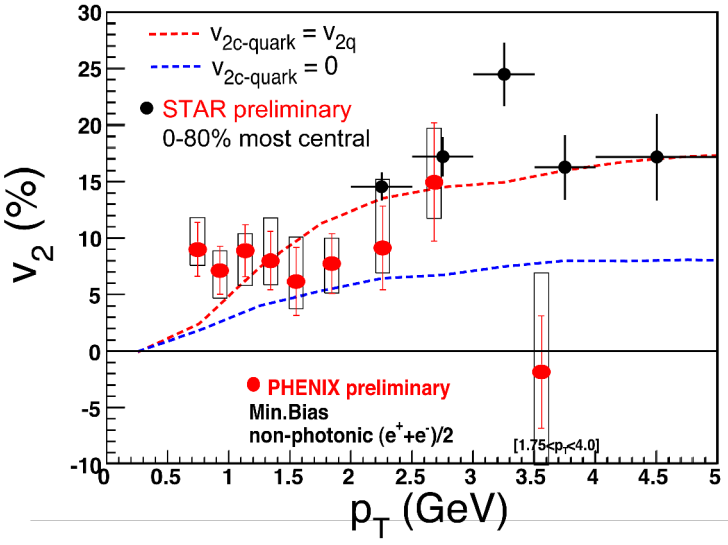


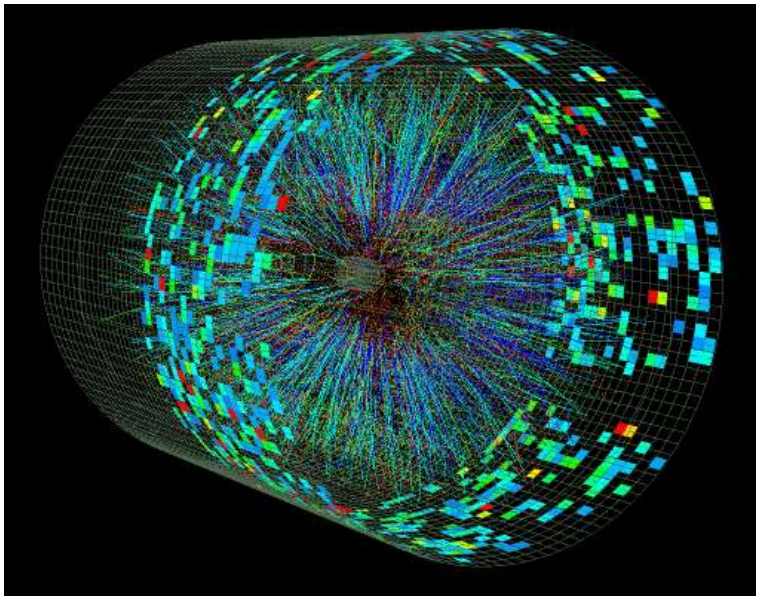

Flow for non-photonic electrons consistent with those of light mesons

Favors scenario in which charm quark flows as light quarks

Strong coupling of charm quark to the medium

*See talk, Laue(5a)*

# Future Outlook



- Rich physics still on tape: Half of year 4 Au+Au, 80% of year 5 Cu+Cu statistics still to be processed
- Future runs:
  - Full EMC barrel installed and ready for use for triggered data over 2 units in $\eta$
  - Full barrel TOF upgrade for identified correlations, resonances, electrons
  - DAQ1000 upgrade of DAQ to remove deadtime, increase dataset size
  - Forward Meson Spectrometer upgrade for definitive measurements on CGC
  - Heavy Flavor Tracker for definitive measurements of open charm

*See talk, Schweda (11a)*

# Conclusion

- Wealth of new data: Real quantitative progress
  - Length dependence: Cu+Cu
  - Fragmentation dominance: particle ID to 10 GeV/c
  - Correlations: clear dijets and beginning of $\gamma$-jet
  - Heavy flavor: direct $D^0$, electron $R_{AA}$ and $v_2$

- Increasing constraints, emerging puzzles in picture of radiative energy loss
  - Can we move towards precision, and perhaps place an upper bound on the energy density?
    - From this, may be able to determine the number of degrees of freedom:
      Müller, Rajagopal, hep-ph/0502174
  - Suppression and $v_2$ of heavy flavor: what is the origin? Can this be reconciled with the suppression patterns of light hadrons?

# STAR Talks in Parallel Sessions

**STAR**

| | |
|---|---|
| • O. Barannikova (1a) | Results of identified pions, kaons, (anti)-protons up to transverse momentum of 12 GeV/c from STAR |
| • B. Mohanty (1b) | Particle production at forward rapidity in d+Au and Au+Au collisions with STAR experiment at RHIC |
| • X. Cai (1b) | Measurements of nuclear modification factor and elliptic flow of $\phi$ with STAR |
| • M. D. Oldenburg (2a) | Event-wise azimuthal anisotropy ($v_2$) for identified hadrons |
| • G. Wang (2a) | Anisotropic flow in AuAu and CuCu at 62 and 200 GeV |
| • T. Dietel (3b) | Azimuthal correlations of high-$p_T$ photons and hadrons in Au+Au collisions at RHIC |
| • D. Magestro (3b) | High-$p_T$ $\Delta\phi$ correlations with increased statistics in STAR |
| • J.G. Ulery (3c) | Full reconstruction of charged hadrons correlated with high $p_T$ $h^{+-}$, $\pi^+$, $\pi^-$, protons and antiprotons from STAR |
| • Z. Chajecki (4a) | Identical particle correlations in STAR |
| • P. Chaloupka (4a) | Non-identical particle correlations at 62 and 200 GeV at STAR |
| • C.A. Pruneau (4c) | Probing collision dynamics with fluctuation and correlation studies at RHIC |
| • S. Salur (5a) | System size dependence of strangeness production |
| • F. Laue (5a) | Measurement of non-photonic single electron $v_2$ at STAR |
| • J. Bielcik (5c) | Centrality dependence of heavy flavor production from single electron measurement in 200 GeV Au+Au collisions |
| • H.-B. Zhang (5c) | Open charm production in 200 GeV Au+Au collisions |
| • K. Schweda (11a) | A heavy flavor tracker for STAR at RHIC |

# The STAR Collaboration

**U.S. Labs:**
Argonne, Lawrence Berkeley, and Brookhaven National Labs

**U.S. Universities:**
UC Berkeley, UC Davis, UCLA, Caltech, Carnegie Mellon, Creighton, Indiana, Kent State, MIT, MSU, CCNY, Ohio State, Penn State, Purdue, Rice, Texas A&M, UT Austin, Washington, Wayne State, Valparaiso, Yale

**Brazil:**
Universidade de Sao Paolo

**China:**
IHEP - Beijing, IPP - Wuhan, USTC, Tsinghua, SINAP, IMP Lanzhou

**Croatia:**
Zagreb University

**Czech Republic:**
Nuclear Physics Institute

**England:**
University of Birmingham

**France:**
Institut de Recherches Subatomiques Strasbourg, SUBATECH - Nantes

**Germany:**
Max Planck Institute – Munich
University of Frankfurt

**India:**
Bhubaneswar, Jammu, IIT-Mumbai, Panjab, Rajasthan, VECC

**Netherlands:**
NIKHEF/Utrecht

**Poland:**
Warsaw University of Technology

**Russia:**
MEPHI – Moscow, LPP/LHE JINR – Dubna, IHEP – Protvino

**South Korea:**
Pusan National University

**Switzerland:**
University of Bern

# STAR Posters

**STAR**

- Section 1
  - A. Mischke (18): High transverse momentum inclusive neutral pion production in d-Au and p-p collisions at RHIC
  - D. Mishra (19): Measurements of $\Delta$ and K* production in d+Au collisions at 200 GeV
  - J.H. Putschke (24): Universal behavior of the nuclear modification factor at RHIC?
  - T.A. Trainor (31): Two-particle correlations from 200 GeV p-p collisions: a precision reference for A-A collisions at RHIC
  - G. van Buren (33): The ratio $\Sigma^0/\Lambda$ at RHIC
- Section 3:
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